ANALYSIS OF ALEPPO PINE VITALITY AT CHETTABA USING NDVI

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Abstract: The study was carried out in the Chettaba state forest, located in the Constantine region (north-east Algeria), to analyze the dendrometry structure and ecological dynamics of Aleppo pine (*Pinus halepensis* Mill.) stands in a semi-arid Mediterranean context. Three representative stations were selected to characterize structural and physiological variations in the stands, based on field measurements and spectral data from the Normalized Difference Vegetation Index (NDVI) collected in 2024. The dendrometry results show a density of 312-725 stems/ha and a basal area of 22.46-41.32 m²/ha. This progression reflects the accumulation of woody biomass and structural differentiation, with differentiation increasing with increasing competition. Low-density stands are distinguished by higher average diameters (D = 29.85 cm), reflecting mature, well-balanced individuals, while denser stands feature more slender stems and marked competition for light. The height/diameter (H/D) ratio, ranging from 31 to 39, indicates satisfactory mechanical stability and good structural balance. NDVI analysis reveals apparent seasonal variability, with a peak in vegetative vigor in June (mean NDVI = 0.248), followed by a decline in August and October (NDVI ≈ 0.19), linked to summer water stress and leaf senescence. Statistical tests (Friedman and Nemenyi) confirm highly significant differences between periods of active growth and phases of vegetative rest. The convergence of dendrometry and spectral analyses reveals a positive correlation between stand vigor and NDVI, underscoring that medium-density stands (around 400 stems/ha) exhibit the highest productivity and ecological resilience. These results demonstrate the relevance of integrating field measurements and satellite indicators for monitoring forest vitality and the sustainable management of semi-arid Mediterranean ecosystems.

Keywords: Chettaba, *Pinus halepensis*, dendrometry structure, NDVI, forest dynamics, ecological resilience.

1. Introduction

Although Algeria has a vast territory of almost 2.38 million Km^2 (238 million hectares), it only has around 3 million hectares of forest, barely half of which is considered productive. The national afforestation rate remains low, estimated at 1.3% (Kadik, 1987). This forest cover, concentrated mainly in the northern strip of the country, reflects an ecological fragility accentuated by anthropogenic and climatic pressures (Saifi, Mostephaoui & Belhamra, 2023; Khallef & Zennir, 2023).

Aleppo pine (*Pinus halepensis* Mill.) is the dominant species in Algerian forests, occupying an area of around 850,000 ha, far ahead of cork oak (*Quercus suber* L.) and holm oak (*Quercus ilex* L.), which cover 354,000 ha and a few hundred thousand hectares respectively (Rabhi *et al.*, 2023; Sarmoum *et al.*, 2021). These formations are often degraded by recurrent fires, overgrazing, and excessive logging, resulting in a gradual deterioration of stand structure and regeneration (Nedjimi & Guit, 2021; Saifi *et al*., 2023).

In the Constantine region, forest resources remain significant, totaling over 11,000 ha, divided between Aleppo pine (5,173 ha), holm oak (2,258 ha), eucalyptus (1,249 ha), pinion pine (1,226 ha), cypress (785 ha), and various other species (427 ha) (Khallef & Zennir, 2023). This diversity reflects both a high ecological potential and an increased vulnerability to fragmentation and climate change.

This is the background to the Chettaba state forest, located south-west of Constantine, covering an area of 2,398 ha. Classified as one of Algeria's most representative Mediterranean

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pine forests, the Constantine Forestry Department manages it and plays a crucial role in soil preservation, erosion protection, and carbon sequestration (FAO, 2023; Sarmoum *et al.*, 2021).

The aim of this study is twofold: (i) to characterize the dendrometry structure of the Aleppo pine stand through precise measurements of diameter, height and basal area, essential indicators of forest vitality and productivity; (ii) to assess the vigor of the vegetation cover using the normalized vegetation index (NDVI) derived from Landsat 8 satellite images, to appreciate the spatio-temporal dynamics of photosynthesis and leaf density. This integrated approach, combining remote sensing and dendrometry inventory, provides a detailed view of the health of pine plantations and constitutes an ecological reference database for forest managers. Indeed, understanding the structural and physiological parameters of stands is an essential prerequisite for any sustainable management strategy, against a backdrop of climate change and increasing human-induced degradation (Rabhi *et al.*, 2023; Sarmoum *et al.*, 2021; Saifi *et al.*, 2023).

The joint analysis of dendrometry and NDVI results will enable us to identify vitality gradients, diagnose areas of ecological stress, and support decision-making for the restoration and conservation of Mediterranean forests in northeast Algeria.

2. Methods and materials

2.1. Study site

The present study was conducted in the Chettaba State Forest, located in the southwestern part of the wilaya of Constantine (north-eastern Algeria). It covers a total area of 2,398 ha 94 a and spans a diverse relief with an average elevation of 865 meters. The extreme altitudes range from 652 to 1,104 meters, corresponding to coordinates (X = 839, Y = 344) and (X′ = 839.9, Y′ = 340.3).

The climate ranges from semi-arid to sub-humid, with an average annual rainfall of 670-800 mm and an average temperature of 18°C. Summer temperatures often exceed 35°C, while winter lows are around 1-3°C. These conditions directly affect the growth and health of Aleppo pine, the dominant species in Chettaba stands (Quézel & Médail, 2021; Slimani *et* al., 2023).

The forest is located on topographic sheet No. 17 of Constantine (scale 1:200,000), between 36°19′4″N and 6°28′36″E. It contains mixed stands of *Pinus halepensis* Mill., *Quercus ilex* L., and *Juniperus oxycedrus* L., representative of the Mediterranean ecosystems of North-East Algeria (Yahi, 2021).

2.2. Sampling and dendrometry measurements

Three key altitudinal stations were chosen along a topographical gradient (Table 1).

Table 1. Characteristics of the stations studied.

Station	Altitude (m)	Topographical position	Stand type
1	625	Lower slope	Dense pine forest
2	992	Average altitude	Mixed pine forest
3	1 018	Upper slope	Sparse pine forest

At each station, a comprehensive dendrometry inventory was conducted according to the guidelines of Rondeux (1999) and Alemu *et al.* (2023).

Measured parameters include:

- Diameter at breast height (D, in cm) measured with a forestry compass;
- Total height (H, in m) estimated by a mobile inclinometer (Android app),
- Guaranteeing accuracy in line with dendrometry standards (Rahim *et al.*, 2022; Magnuson *et al.*, 2024).
- Basal area (G, m²/ha) calculated using the formula:

$$G = \sum_{i=1}^{n} \Pi \frac{Di^2}{4S}$$

where S is the plot area (ha). These variables describe the stand's vertical and horizontal structure and evaluate its potential productivity.

2.3. Image processing and NDVI calculation

2.3.1. Acquisition and pre-processing

Landsat 8 OLI/TIRS Collection 2 (level 2A) images from June 22, July 25, August 29, September 12, and October 14, 2024, were obtained from the Google Earth Engine (GEE) platform.

Radiometric and atmospheric pre-processing were performed using corrected surface reflectance (SR) bands (Zhang *et al.*, 2021)

Cloud and sand masking were applied using the integrated QA_PIXEL mask. Pixels with a red reflectance value greater than 0.25 and a difference (NIR - RED) less than 0.05 were excluded to eliminate mineral or burnt surfaces. The resulting images were then visually checked in ENVI 5.1 and exported to ArcGIS 10.8 for classification and extraction of station values.

2.3.2. NDVI calculation

The NDVI (Normalized Difference Vegetation Index) was calculated from the red (R) and near-infrared (NIR) spectral bands using the classic formula (Vermote *et al.*, 2016; Xue & Su, 2017):

$$NDVI = \frac{(PIR - R)}{(PIR + R)}$$

Where PIR and R denote the near-infrared (band 5) and red (band 4) reflectances, respectively.

Values range from -1 to +1, with values over 0.4 indicating a dense, active canopy, and values below 0.2 suggesting water stress or low leaf density.

Missing values (cloudy areas or excluded pixels) were filled in using spatial bilinear interpolation in ENVI, then validated by a temporal moving average in GEE.

This index is widely recognized for its effectiveness in assessing the vigor, biomass, and photosynthetic activity of plant cover (Huete *et al.*, 2022). High values indicate dense vegetation, while low values suggest water stress or forest cover degradation.

2.4. Statistical Analysis

The NDVI values collected from the three stations were analyzed using analysis of variance (ANOVA), followed by Friedman's nonparametric test, to identify statistically significant differences between sites. All analyses were performed using XLSTAT 2023.

To analyze temporal trends in NDVI, the nonparametric Mann-Kendall test (Mann, 1945; Kendall, 1975) was applied to the monthly time series. This test, particularly suitable for identifying monotonic trends in environmental data, has been widely used in hydrological and environmental research (Yue *et al.*, 2020; Li *et al.*, 2022). A positive value indicates an upward trend in NDVI (greater vitality), while a negative value indicates a decline in plant vigor.

3. Results and discussion

3.1. Dendrometric structure of Aleppo pine stands

Dendrometric analysis of the three plots studied in the Chettaba forest shows structural variability in terms of density, basal area, and average tree size (Table 2).

Table 2. Dendrometric parameters of the three *P. halepensis* plots in the Chettaba forest.

Plot	D (cm)	H (m)	H/D	gh (m²)	g (m²)	(g–gh) (m²)	N/ha	G (m²/ha)
1	29.85	9.03	31.44	0.070	0.072	0.002	312	22.46
2	25.33	9.50	39.76	0.050	0.055	0.005	438	24.09
3	26.54	10.03	38.56	0.055	0.057	0.001	725	41.32

The results indicate a gradual increase in stand density, from 312 stems/ha in plot 1 to 725 stems/ha in plot 3. This rise in density is also reflected in the total basal area (G), which increases from 22.46 to 41.32 m²/ha, showing a significant buildup of woody biomass. (Alemu *et al.*, 2023; Bravo-Oviedo *et al.*, 2023).

Plot 1, at low density, contains the most developed individuals (D = 29.85 cm), reflecting a more advanced stage of forest succession. In contrast, plot 3, at high density, represents a young stand with intense resource competition (Sterba, 2019). This structure reflects the dynamics typical of Mediterranean Aleppo pine forests, where young stands show rapid but less balanced growth in diameter and height (Calama *et al.*, 2020).

The gap (g-gh) is less than 0.005 m² in all three plots, indicating a high level of internal uniformity among the stems and confirming consistent growth and minimal diametral variability within the stands. This finding supports Pretzsch's (2014) observations that regular stands demonstrate greater space-occupation efficiency and structural stability.

The variability of dendrometric parameters observed across the three plots reflects the significant influence of stand density, edaphic conditions, and water availability on Aleppo pine dynamics.

Low-density stands, such as plot 1, exhibit sustained diametral growth and greater mechanical stability, which promote the production of large timber. Dense stands (plot 3), however, are marked by faster height growth and increased sensitivity to abiotic and biotic stresses (Ruiz-Peinado *et al.*, 2017; De Cáceres *et al.*, 2020).

Basal area (G), directly correlated with productivity, increases with tree density. This trend was also observed by Benhassine *et al.* (2021) in the Aleppo pine forests of Algeria's eastern Tell, where young stands (600-800 stems/ha) had land areas exceeding 40 m²/ha. These values are comparable to those of plot 3 in the present study, confirming that the Chettaba forest follows a dynamic similar to that of other semi-arid sites in north-eastern Algeria.

On a Mediterranean scale, Calama *et al.* (2020) and Bravo-Oviedo *et al.* (2023) reported G values of 20-45 m²/ha for Aleppo pine stands in Spain, depending on age and density. These results agree with ours and confirm that the growth of this species remains strongly affected by the water regime and intra-specific competition.

Under Mediterranean conditions, Vargas-Larreta *et al.* (2021) demonstrated that moderate-density stands (~400 stems/ha) provide an optimal balance between diameter growth and structural stability. Conversely, very dense stands tend to develop high H/D ratios (>38), as seen in plots 2 and 3 of our study.

The work of Cáceres *et al.* (2020) also demonstrated that the resilience of Mediterranean forests to climate change largely depends on structural diversity. The results from the Chettaba forest clearly illustrate this: less-dense stands (plot 1) exhibit a more balanced structure and potentially greater resilience.

Finally, the values measured in our study (G = 22-41 m²/ha; N = 312-725 stems/ha; H/D = 31-39) fall within the ranges reported by Quézel et Médail (2003) for natural stands of *Pinus halepensis* in the semi-arid zones of the Maghreb, confirming the ecological coherence of these forests with the regional bioclimatic context. In summary, the stand structure of the Chettaba forest is similar to that observed in

other Aleppo pine forests around the Mediterranean.

The high basal area (G > 40 m²/ha) in dense sites indicates a forest productivity similar to that of the Spanish and Moroccan massifs. Meanwhile, medium-density stands (400 stems/ha) provide a balance between growth, stability, and ecological resilience. This internal heterogeneity is a key asset for the sustainability and multifunctionality of Mediterranean forest ecosystems (Alemu *et al.*, 2023; Sterba, 2019; Vargas-Larreta *et al.*, 2021).

3.2. NDVI

The results for 2024 (Table 3) clearly demonstrate the marked temporal variability in NDVI values for Aleppo pine (*Pinus halepensis*), reflecting seasonal fluctuations in photosynthetic activity and canopy vitality.

Table 3. Descriptive statistics of NDVI values for Aleppo pine (2024).

NDVI Date	Observations	Min	Max	Average	Gap Type	Std. Dev
22/06/2024	21	0.201	0.324	0.248	0.034	0.008
25/07/2024	21	0.192	0.288	0.229	0.027	0.007
29/08/2024	21	0.151	0.241	0.193	0.025	0.006
12/09/2024	21	0.165	0.257	0.211	0.024	0.005
14/10/2024	21	0.137	0.249	0.194	0.031	0.007

Friedman's non-parametric analysis of variance (Fig. 1) revealed a highly significant difference between the months of observation ($p < 0.0001$), confirming that the NDVI values do not come from the same statistical population. This result reflects the strong influence of seasonal climatic conditions on vegetation dynamics.

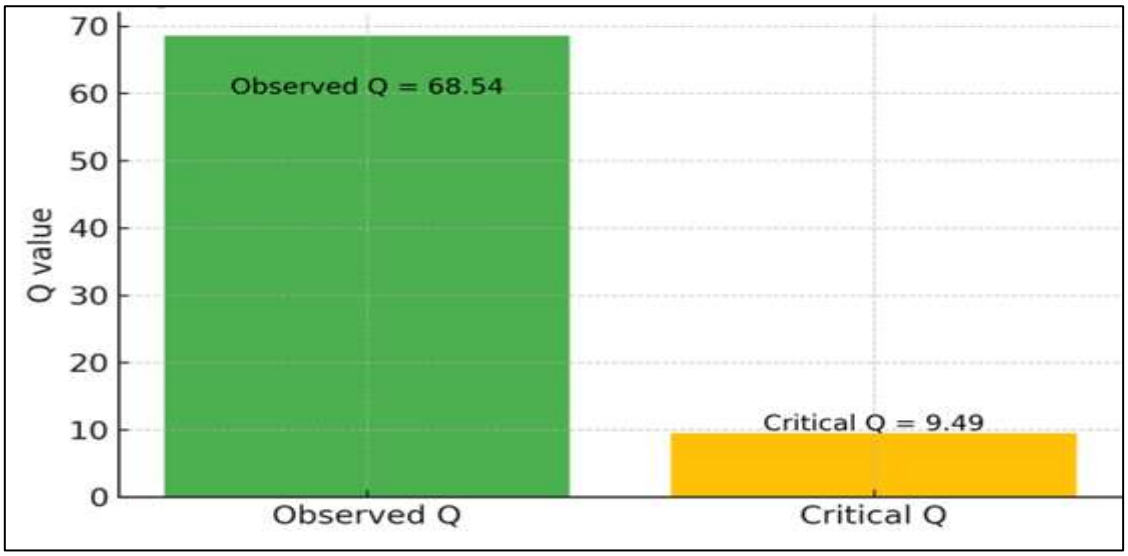

Figure 1. Friedman's test of NDVI values for Aleppo pine (2024).

The highest NDVI values were recorded in June (0.248), corresponding to the period of maximum physiological vigor for Aleppo pine. This period coincides with still-favorable thermal and hydric conditions, stimulating chlorophyll activity and leaf density. Conversely, the lowest values observed in August (0.193) and October (0.194) correspond to the gradual decline in active biomass, a direct consequence of summer drought, cumulative water stress, and the onset of leaf senescence, as shown by the statistical distribution detailed in Table 4 and Figure 2.

Table 4. Pairwise multiple comparison of NDVI values using the Nemenyi/Two-Way test (2024).

Sample	Workforce	Sum of Ranks	Average Rank	Groups
22/06/2024	21	30.000	1.429	A
25/07/2024	21	36.000	1.714	A
29/08/2024	21	65.000	3.095	B
12/09/2024	21	87.000	4.143	BC
14/10/2024	21	94.000	4.476	C

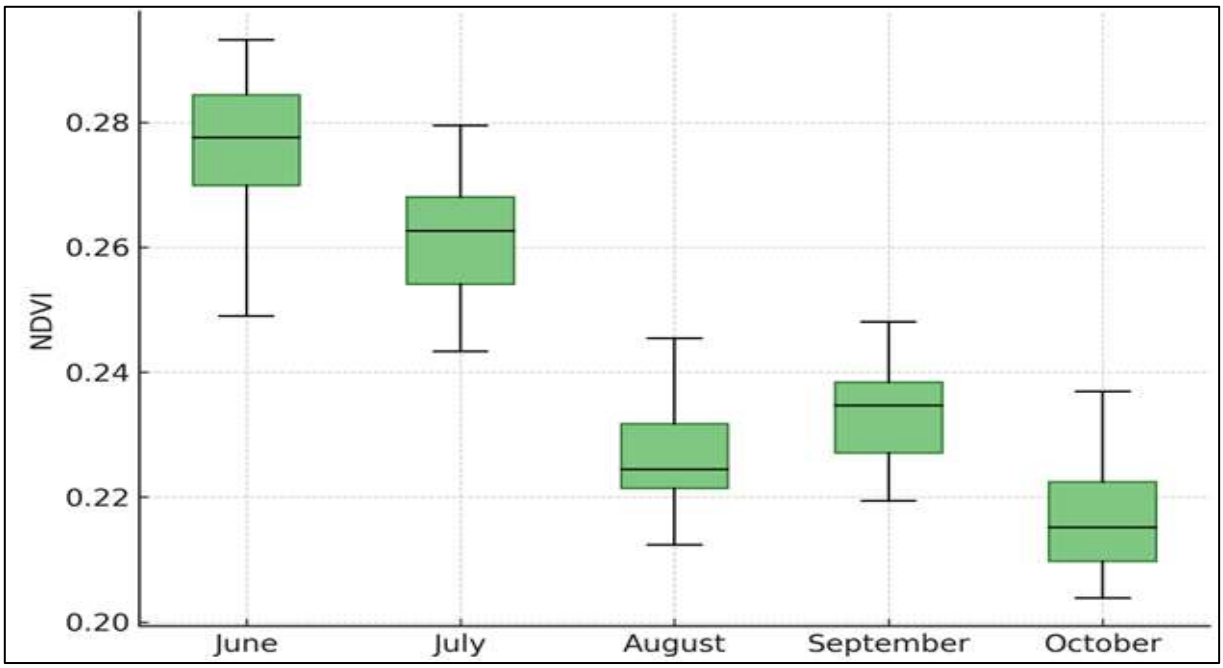

Figure 2. Box plots of NDVI values by month (2024).

These trends confirm the observations of Rouached *et al.* (2023), who also highlighted the seasonal dynamics of NDVI in Aleppo pine in semi-arid Mediterranean zones, marked by a sharp drop in values during the dry summer.

According to Rondeux (1999), NDVI fluctuations are closely linked to stand structure and canopy density: a reduction in leaf density, often due to water deficit or defoliation, results in a significant drop in NDVI.

Furthermore, Yahi (2021) notes that in the forests of northeastern Algeria, interannual variations in NDVI directly reflect local ecological constraints, especially water availability and substrate type. With this in mind, the 2024 results align with a recurring ecological pattern already observed in 2020 (Haddad *et al*., 2021), where the lowest values also occurred during late summer and autumn months. This consistency indicates a moderate yet persistent resilience of Aleppo pine stands to the repeated drought conditions typical of the continental Mediterranean climate.

Comparisons with other studies support this seasonal pattern. Vargas-Larreta *et al.* (2021) have shown that in dry conifer ecosystems, NDVI is closely linked to canopy structure and soil water availability. Similarly, Sa *et al.* (2023) observed that the resilience of Mediterranean forests is directly connected to NDVI's ability to recover after the dry season.

The notable decrease in NDVI from July to October 2024, as shown in Figure 2, can be attributed to a combination of summer water stress, increased solar radiation, and reduced active leaf area. This supports the findings of Schütz and Rosset (2020) regarding the sensitivity of Mediterranean conifers to extended drought.

In summary, the 2024 results show a stable yet vulnerable seasonal cycle in Aleppo pine primary productivity. Once again, NDVI seems

to be a dependable indicator of forest health, sensitive to climate variation, and valuable for tracking spatial and temporal changes in the health of Mediterranean forests.

4. Conclusion

The study conducted in the Chettaba forest highlights the structural diversity and ecological resilience of Aleppo pine stands. Dendrometry analysis shows significant differences between plots, indicating the impact of density and site conditions on tree growth and stability. Less dense stands exhibit balanced growth and stronger resistance to environmental stresses, while denser stands grow more quickly but are more vulnerable to climatic stresses.

Seasonal variations in NDVI confirm Aleppo pine's strong dependence on water and temperature conditions. The highest values occur during the active growth period, while the decline at the end of summer shows the effect of water shortage and summer stress. This pattern reflects the species' functional adaptation to changes in the Mediterranean climate.

Overall, the results underline the complementarity of dendrometry and spectral approaches for assessing the vitality and productivity of Mediterranean forests. The Chettaba forest thus emerges as a representative and resilient ecosystem, whose sustainable management relies on detailed knowledge of its structure and seasonal functioning.

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